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Electrophysical, Magnetoresistivity and Magneto-optical Properties of Multilayer Materials Based on Nanocrystalline and Amorphous Films

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In work is presented to the results of complex investigate of phase formation, thermal resistivite, magnetoresistive and magneto-optical properties of multilayers based Fe and Pd, Ag or Ge, which obtained by sequential condensation of the layers with following thermal annealing. Investigation of phase formation processes of thin film systems and established of correlation between this processes and above-mention physical properties.

Keywords: Double-layer film, Multilayer, Phase formation, Annealing, Thermal coefficient of resistivity, Magnetoresistance, MOKE.

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1. INTRODUCTION

Development magnetoelectronic and sensory device closely related to the search for new functional materials as magneto-heterogeneous multilayers and granular alloys. Film systems based on of ferromagnetic (Fe, Co) and paramagnetic metal (Pd, Ag) and semiconductors (Ge) layers - this is interesting objects in terms of practical use to create magnetic high-density recording medium [1-5], magneto-optical elements and systems of spin-valve electronics [6, 7]. In forming such apparatus systems, special attention is paid to the stability of performance characteristic at the influence of temperature and magnetic field. In film systems size effects and processes of phase formation at the influence of temperature are of the essence, that changing the number of fragments, the thickness of individual layers and the processing temperature ranges you can get materials with reassigned electrical and magnetic parameters. Currently received considerable information about the structural and magnetic properties of multilayer films based on Fe and Pd, Ag or Ge. The question correlation between the phase composition and electrophysical (thermal coefficient of resistance (TCR), magnetoresistive (magnetoresistance (MR) and giant magnetoresistance (GMR)) properties and magneto-optical Kerr effect (MOKE) are insufficiently known such materials obtained by condensation layer followed by annealing on the temperature range 300 - 900 K.

The above and determined the aim of this work, it was to study the influence of processes of formation of thermoresistive (in our previous work [8] the results of research strain effect), magnetoresistive and magneto-optical properties of multilayer film materials Pd/Fe, Ag/Fe and Ge/Fe.

2. METHODIC AND TECHNIC OF EXPERIMENT

Film materials based on Fe and Pd or Ag(Ge), formed as multilayer (periodic film systems Pd/Fe) or double- and three-layer films (systems Ag/Fe and Ge/Fe) were obtained by thermal evaporation by sequential condensation of the layers with following thermal annealing using standard vacuum (residual pressure of the atmosphere $p = 10^{-3} - 10^{-4}$ Pa) and high-vacuum ($p = 10^{-5}$ Pa) apparatus. To study of processes the phase formation and crystal structure used methods of electron microscopy and electron diffraction (TEM-125 K). Annealing of samples during the three cycles on a "heating - cooling" on the temperature range 300 – 900K. The calculation of TCR based on the temperature dependence of resistivity (ρ) by the ratio

$$TCR = \beta = 1/\rho_i \cdot (\Delta\rho/\Delta T),$$

where ρ_i – initial resistivity of the sample; ΔT – temperature range.

The study of magnetoresistive properties at the three geometries was carried: perpendicular ($B \perp I, S$), parallel ($B \,||\, I, S$) and transverse ($I \perp B \,||\, S$), where B – induction of the magnetic field; I – electric current and S – substrate. To calculate the magnetoresistance ratio used

$$MO = [R(B) - R(0)]/R(0) = \Delta R/R(0),$$

where $R(B)$ and $R(0)$ – the resistance of the sample in an external magnetic field and in his absence.

The study of magneto-optical properties by the method based on the MOKE in longitudinal geometry, where the magnetization vector lies in the plane of sample.

3. EXPERIMENTAL RESULTS

3.1 Phase formation processes

Investigation of phase formation in the systems Pd/Fe showed that the films during by sequential condensation of the layers condensation is the formation of disordered fcc-PdFe phase as a solid solution (s.s.) (Fig.1a), which due to condensation-induced diffusion processes of ordering with the formation fct-PdFe phase during annealing on the temperature range $\Delta T = 300 - 800$ K . As a result, decrease the phase transition temperature fcc-PdFe → fct-PdFe compared to bulk samples of approximately 300 K (for multilayer) and at 200 K (for double-layer samples). From the value of parameters lattice ordered phase of fct-PdFe follows that the value (c/a – 1) = 0,047 – 0,048, which corresponds to the degree of ordering S = 0,86 – 0,90.

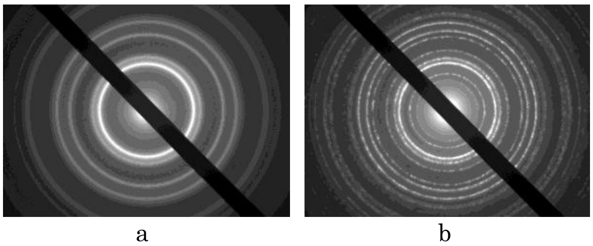

Fig. 1 – Diffraction patterns of multilayers $Pd(1,1)/Fe(0,9)]_5/S$, which obtained at 300 K (a) and annealed to 780 K (b)

Summary results of X-ray and electron-diffraction studies are presented as diagrams (Fig. 2).

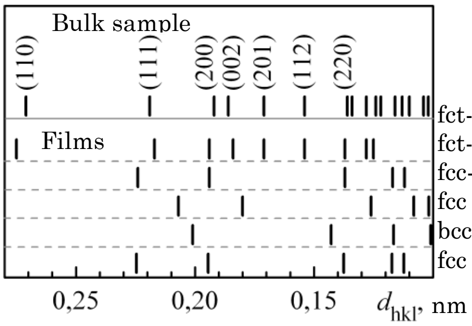

Fig. 2 – Generalized diagram of diffraction studies

The phase composition of the single-layer films non-annealing responsible bcc-Fe and quasi-amorphous Ge, which at 680 K becomes crystalline Ge (qa-Ge → a-Ge). During the condensation of double- and three-layer films is formed limited s.s. (Fe, Ge) based on bcc-Fe, which causes increase of the lattice parameter of bcc-Fe on $\Delta a = 0{,}009$ nm. Annealing of this samples carried to decomposition of s.s. and causes of solid-phase reaction and formation at $T = 680$K crystallites phase $FeGe_2$. In film systems Fe/Ag/Fe observed formation of limited s.s. based on bcc-Ag, although to a large extent preserved the individuality of separate layers.

3.2 Electrophysical properties

Results of experimental investigation of the temperature dependence resistivity and TCR of double-layer films and multilayers Pd/Fe indicating that the electrical properties of fcc-FePd significantly depends on the relationship of thickness Pd and Fe. At the transition from double-layer film to multilayer, the dependence $\rho(T)$ gradually changes and becomes practically linear (Fig. 3 a, b). This can be explained decrease the concentration of crystall structure us a result of their autohealing in the lower layers at the condensation next layer, that seen on the temperature dependence resistivity at the first annealing cycle.

Typical temperature dependence of resistivity and TCR for systems based on Ge and Fe is shown in Fig. 3 c. Its characteristic feature is the large values of ρ and, therefore, relatively small value of β.

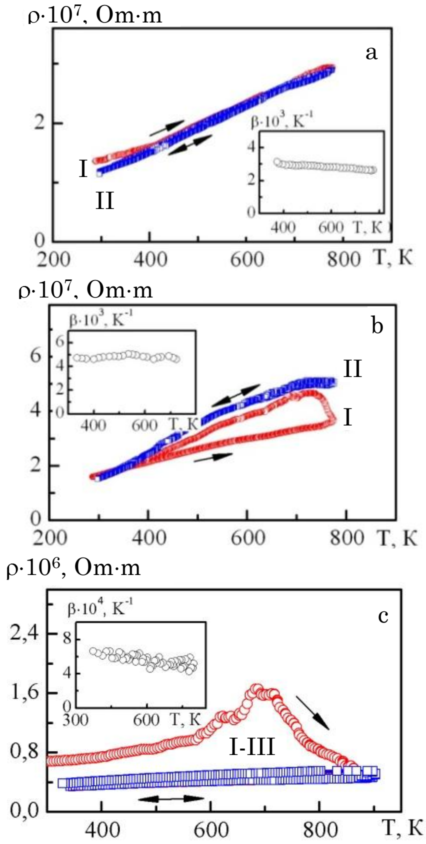

Fig. 3 – Temperature dependence resistivity and TCR (on the inserts) for film systems $[Pd(1,1)/Fe(5)]_5/S$ (a), $[Pd(0,6)/(Fe(0,6)]_{10}/S$ (b) and qa-Ge(70)/Fe(30)/S (c).
I, II and III – annealing circles

Maximum on the curve at 680 K can be explained by processes of phase formation in the system of crystalline of phase $FeGe_2$.

Research electrophysical properties of film systems based on Ag and Fe indicate the relative great value ρ and small value β, which can be explained by the formation of limited s.s. Fe atoms in lattice fcc-Ag.

3.3 Magnetoresistive properties

Investigation of magnetoresistive properties indicate that at the transition from double-layer films to multilayers leads to the occurrence additional scattering mechanisms of electrons – at the interface (in the case of individual of separate layers) or at the magnetic interfaces (in the case of formation solid solution). In second case the electrons scattering is not at real interfaces, but on the magnetic moments of atoms ferromagnetic and induced magnetic moments of atoms non-magnetic materials. In multilayers as opposed to single-layer can be stabilized granular state, magnetic interfaces formed or intermetallic inclusions. In such a case can be realized spin-dependent scattering of electrons and the system will have antiferromagnetic ordering.

The research magnetoresistive property of multilayers based on Pd and Fe established that the dependence of MR from induction of external magnetic field is isotropic and its value, as the value of resistance, decreases monotonically with increasing induction.

In non-annealing and annealed to 780 K multilayers based on films Pd and Fe observed signs of GMR (Fig. 4). Value of MR increased by 2 – 4 times as the number of fragments increased from 3 to 10. In fct-PdFe ordered phase compared with non-anneling systems value MR increase in 3,0 – 3,5 times and has value 0,35 – 0,40% for the longitudinal geometry. It is also shown that in double-layer samples based on Pd and Fe at the concentration of Fe atoms c_{Fe} > 55 – 80 at.% and $d_{Fe} > d_{Pd}$ is shown anisotropic MR, which is due to the influence of ferromagnetic component of the sample, thus increasing the total film thickness. In multilayers $[Pd/Fe]_n$ with the number of fragments n = 3 – 10 before and after annealing to T = 780 K there are signs of GMR, and the value of magnetoresistance increases by 0,02 – 0,16%, due to transition of disordered fcc-PdFe phase fct-PdFe ordered phase and, to some extent, recrystalline processes, with changing concentrations of palladium (c_{Pd} = 35 – 65 %) value MR is (0,20 – 0,36)% at the T = 300 K and (0,10 – 0,60)%. with T = 780 K.

Investigation of magnetoresistive properties of films Fe(10)/Ge(x)/Fe(10), where x = 2 – 10 nm shows that the maximum value MR = 0,38 % observed in the longitudinal geometry for annealed to 800 K samples of thickness nonmagnetic layer x = 2,8 nm, which explained by formation under such conditions (concentration and temperature) magnetic phase $FeGe_2$. In samples Fe(10)/Ge(3)/Fe(10) after annealing to 800 K

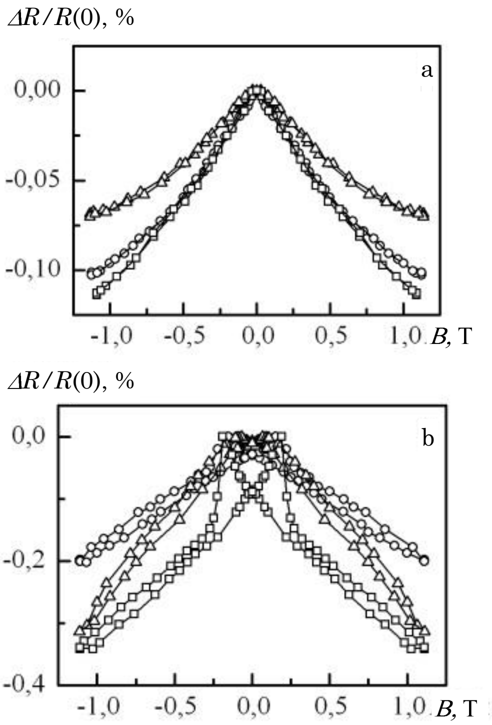

Fig. 4 – Field dependence of MR at T = 300 (a) and 780 K (b) for multilayer $[Pd(1,1)/Fe(0,9)]_5$/S. The total concentration of atoms Fe – 50 at.%. Measurement geometries: parallel (○), perpendicular (△) and transverse (□)

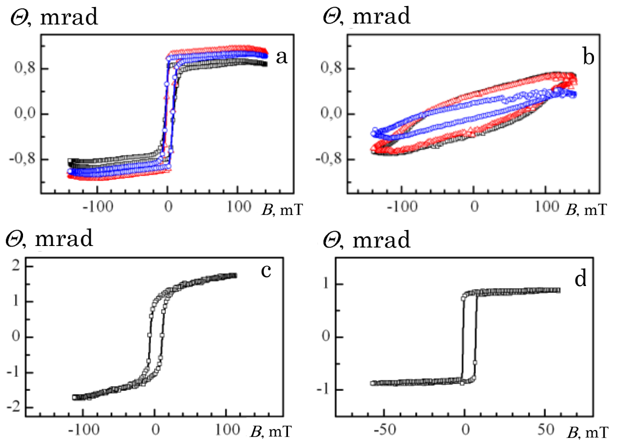

Fig. 5 – Dependence of the Kerr angle Θ of the applied magnetic field for films $[Pd(1,1)/Fe(1,1)]_5$/S (a, b) i Fe(10)/Ge(10)/Fe(10)/S (c, d): T = 300 (a); 600 (c) and 800 K (b, d). □ – 0°; △ – 45°; ○ – 90°

there are signs of GMR. With increasing Ge layer thickness values MR decrease to 0,030 – 0,001% and the coercive field from 42 to 15 mT (not annealed), from 40 to 20 mT (T = 600 K) and from 70 to 8 mT (T = 800 K). It is known [6] that the Ge atoms rapidly diffuse into the layers of Fe.

Value MR in three-layer film systems Ag(x_1)/Fe(3)/Ag(x_2)/S, where x_1 = 1, 2 or 5 nm; x_2 = 5, 4 or 1 nm in the longitudinal geometry is MR = 0,30 – 0,50%. In the systems Ag(5)/Fe(3)/Ag(1)/S by changing the magnetic field from – 0,4 to + 0,4 T signs of GMR is observed.

Investigation of magneto-optical properties of thin film systems using MOKE indicate on their dependence from the phase composition, the atomic and magnetic ordering, which makes a change coercivity and its anisotropy at the phase formation and the dependence of the saturation field from the thickness nonmagnetic layer. Found that in systems based on films Fe and Pd, Ag and Ge observed dependence of the Kerr angle Θ of the magnetic field in the form of step hysteresis loop (Fig. 5), what indicating realizations of two magnetic states and the performance of the functional element of apparatus systems on the magnetic field.

4. CONCLUSIONS

Investigation of the mutual connection between the processes of formation and thermal, magnetoresistive and magneto-optical properties of thin film systems indicate that the by sequential condensation of the layers with following thermal annealing from 300 to 900K occur in systems: processes of formation based on the phase fcc-PdFe as s.s.(Pd, Fe) fct-PdFe ordered phase due to condensation processes-stimulated diffusion (film Pd/Fe); partial stabilization including limited (Fe, Ag) while retaining a large degree of individuality of the separate layers (film Ag/Fe) and the formation and subsequent decay. Including (Fe, Ge) to form of $FeGe_2$ phase (film Ge/Fe), which significantly affect the thermal properties and magnetoresistive thin film systems. It is shown that due to phase formation processes in film systems the values TCR are (3,8 – 7,5) $\cdot 10^{-4}$

K^{-1} (two-layer system Pd/Fe) and $(1,8 - 3,0) \cdot 10^{-3}$ K^{-1} (multilayers $[Pd/Fe]_n$); $(1,0 - 1,1) \cdot 10^{-3}$ K^{-1} and $(4,2 - 6,8) \cdot 10^{-4}$ K^{-1} (double- and three-layer system based on films Ag and Fe or Ge and Fe, accordingly). In multilayers $[Pd/Fe]_n$, two- and three-film systems based on Ag and Fe or Ge, and Fe (the thickness of individual layers of $d = 0,6 - 10$ nm) before and after annealing, there are signs of GMR, and the value of MR is increase at 0,05 – 0,15%. All the above allows us to consider such systems as sensitive elements of multi-sensor temperature and magnetic field.

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REFERENCES

1. K. Sato, K. Aoyagi, T.J. Konno, *J. Appl. Phys.* **107**, 024304-1 (2010).
2. D. Pecko, K.Z. Rozman, P.J. McGuiness, *J. Appl. Phys.* **107**, 09A712-1 (2010).
3. J. Lyubina, O. Gutfleisch, O. Isnard, *J. Appl. Phys.* **105**, 07A717-1 (2009).
4. T. Phalet, M. J. Prandolini, *Phys. Rev. B.* **71**, 144301 (2005).
5. F. Liu, *Applied Physics A*, **81**, 4343 (2005).
6. D. Sellmyer, R. Skomski, *Advanced magnetic nanostructures* (New-York: Springer: 2006).
7. M.F. Toney, J.A. Borchers, K.V. O'Donovan, C.F. Majkrzak, D.T. Margulies, E.E. Fullerton, *Appl. Phys. Lett.* **86**, 506-1 (2005).
8. I.P. Buryk, D.V. Velykodnyi, L.V. Odnodvorets, I.E. Protsenko, E.P. Tkach, *Tech. Phys.* **56**, 232 (2011).